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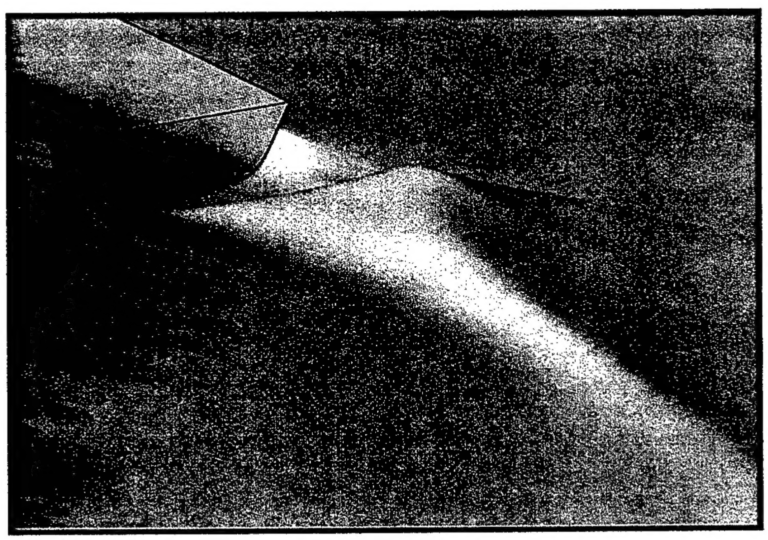
Research and Development Report

COMPUTATION OF HIGH-SPEED TURBULENT FLOW ABOUT A SHIP MODEL WITH A TRANSOM STERN



by

H.J. Haussling
R.W. Miller
R.M. Coleman

This report is a modified version of a paper presented at the ASME Fluids Engineering Division Summer Meeting, June 1997.

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H.J. Haussling, R.W. Miller, and R.M. Coleman

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This report is a recent paper presented by the authors, slightly modified to include comparison with more recently measured data. The steady flow about a surface ship model with a transom stern moving at high speed is analyzed. Viscous effects are included through the use of a numerical solution of the Reynolds-averaged Navier-Stokes (RANS) equations subject to nonlinear free-surface boundary conditions. The $k - \epsilon$ turbulence model is employed. The structured grid maintains its hull boundary-layer resolution into the wake. This assures the capturing of the strong viscous/free-surface interaction of the boundary-layer wake with the stern wave field. This interaction is demonstrated by comparison with results of inviscid computations. Comparisons with measured data are also presented. The results represent a step forward in a long history of progress on the challenging problem of the computation of flows about transom sterns.

INTRODUCTION

A recent paper (Haussling et al., 1997) presented new results in the form of computed stern wave heights for a ship model with a transom stern. In April 1997, after the March paper submission deadline, new measurements of stern wave heights were obtained during model testing at David Taylor Model Basin.[1] A comparison of the measured data with the previously obtained computational results yields a very powerful validation for the approach of combining RANS equations with free-surface boundary conditions. In order make this important result available to the community, this report, which contains a slightly modified version of the previous paper, is issued. Also included is a direct comparison of the RANS results with potential flow results. Such a comparison was discussed in the previous text but a comparison figure was omitted because of space limitations.

Powerful computer programs have been developed over the years for the computation of the inviscid flow around surface ships. More recently, there has been an effort to develop similar methods which include viscous effects. One popular approach has been to add free-surface boundary condition capabilities to RANS codes. The results of applying several such codes to the Series 60, $C_b = 0.6$, hull were presented and compared at CFD Workshop Tokyo 1994 (Kodama, 1994). It was shown that the combination of RANS technology with free-surface boundary conditions yields a useful capability for surface ship hydrodynamic prediction and analysis.

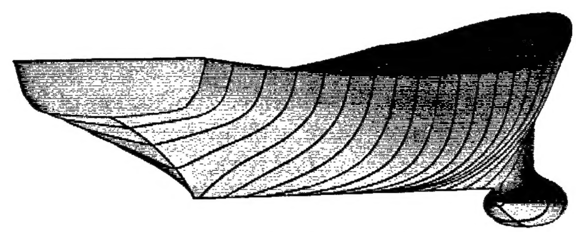

Figure 1. DTMB Model 5415.

Many naval combatants, such as Model 5415 shown in Fig. 1, are high-speed transom stern hulls in contrast to the Series 60 cruiser stern. At a transom (the almost flat surface at the extreme stern in Fig. 1), such as on typical rowboats, the hull terminates abruptly with sharp corners. This contrasts with a cruiser stern, such as on a canoe, where the hull cross section smoothly shrinks to zero area. Navy transom stern hulls are designed so that, at high speed, the flow breaks cleanly from the corner at the base of the transom. This design gives these hulls favorable high speed resistance characteristics (O'Dea et al., 1981). Because of the importance of this type of hull, efforts have been undertaken to apply the surface ship RANS computational capability to the treatment of transom sterns. This application can be important because the details of the flow near the transom are a complex mixture of viscous and nonlinear free surface effects which cannot be analyzed adequately

[1] Ratcliffe et al., report to appear.

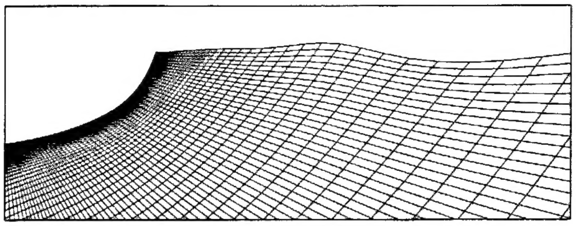

Figure 2. Typical grid cross section at midship.

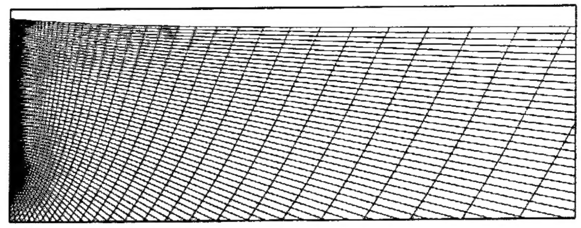

Figure 3. Typical grid cross section upstream or downstream of a cruiser stern hull.

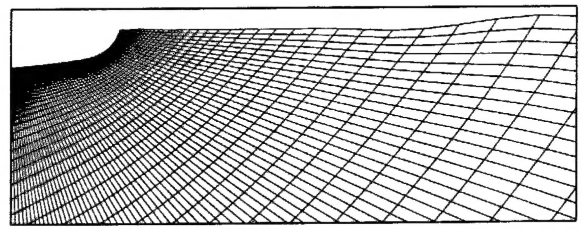

Figure 4. Typical grid section near a transom stern.

with inviscid theories alone. However, the application is not trivial. The accurate treatment of transom sterns has long been an active subject of research even for inviscid computations. Physical and computational aspects of inviscid, high-speed transom stern flows were investigated in the late 70's and early 80's at David Taylor Model Basin (Haussling, 1980; Coleman, 1985). The correct application of boundary conditions for both linear and nonlinear mathematical models was demonstrated. More recently, similar disussions were presented by Raven (1993), Telste and Reed (1993), and Nakos and Sclavounos (1994).

This paper describes a RANS computation of the steady high-speed flow about Model 5415, which is the subject of current experimental measurements for computational fluid dynamics code validation (Rood, 1996). This is a contribution to the broader challenge of unsteady ship hydrodynamics over a wide speed range.

GRIDDING

The use of RANS techniques for transom sterns is hindered by the dependence of state-of-the-art codes on use of highly-structured grids. Use of such grids combined with the geometric complications of the hulls, which transition from fine and deep at the bow to broad and shallow at the stern, present challenges which are different from those presented by cruiser sterns. Application of RANS codes to cruiser sterns have mostly used a one-block approach which includes inflow and outflow sides suitably far upstream and downstream from the hull. The hull and the center plane of symmetry below it form two more sides. The final two sides are the water surface and an often cylindrical outer boundary. A typical grid cross section near a hull is shown in Fig. 2. As the hull thickness shrinks to zero, moving upstream at the bow or downstream at the stern, the hull block side merges with the centerplane and the no-slip condition changes to a symmetry condition. A typical grid cross section upstream or downstream of a hull with a cruiser stern is shown in Fig. 3. For a transom stern hull the same gridding strategy can be used for the upstream and hull regions. This leads to a grid cross section such as that in Fig. 4 in the stern region. However, such a grid cannot be smoothly transitioned at the stern into a grid as pictured in Fig. 3. A transom stern thus demands a somewhat more complex gridding strategy than does a cruiser stern.

Two of the better sets of results for the Series 60 were presented by Tahara and Stern (1994) and by Haussling and Miller (1994) and both used the basic gridding approach discussed above. Recently the method of Tahara and Stern was extended to handle transom sterns as well as cruiser sterns and named CFDSHIP-IOWA (©1995, Univ. of Iowa). The challenge of grid transition at the transom was tackled by breaking the grid into two blocks having different grid structures. Interpolation was used to solve the equations across a block boundary at the transom. The method was applied to the FF1052 hull (Stern et al., 1995) with promising results but problems were encountered and discussed in applying free-surface conditions at the transom.

The current work focusses first on the high-speed regime to initially exclude the complication of flow recirculation behind a wet transom. Use is made of the DTNS3D RANS software, a generalized multiblock code. Some years ago free-surface boundary conditions were added and nonlinear free-surface computations were carried out for the Series 60 hull (Haussling and Gorski, 1995). In the current high-speed transom stern application, grid lines passing the transom are continuous so that resolution of the boundary layer and wake can be maintained in this critical region. This is achieved by creating a downstream starting block which has as its top boundary the undisturbed water level except for directly aft of the transom where there is a trough corresponding to the transom shape. The starting grid cross section downstream of the transom is similar to that shown

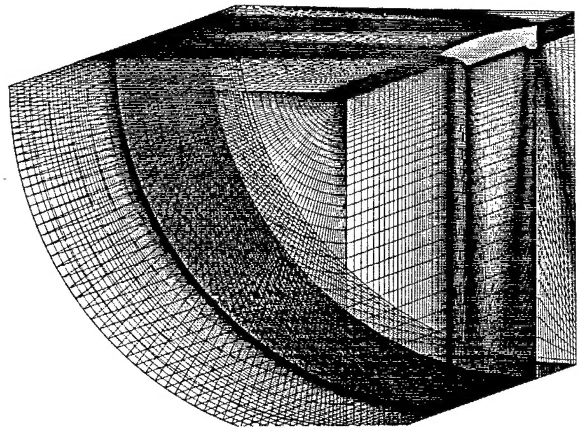

Figure 5. Fine grid (209 X 81 X 65).

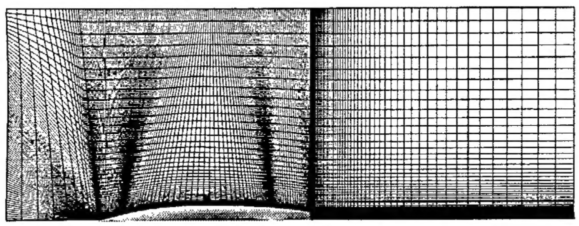

Figure 6. Water surface grid.

in Fig. 4. For high speed operations, with a dry transom, this grid can be adjusted to fit the water surface as its location is computed. For lower speeds, when the transom is wet, another block can be added in the trough and the recirculating flow behind the transom can be computed. In either case resolution of the boundary layer and wake can be maintained as the flow passes the transom.

Views of some grid surfaces are shown in Figs. 5 and 6. For convenience the grid is divided into three blocks. The finest grid contains 209 points in the streamwise direction with 129 on the hull, 16 upstream and 64 downstream. The cross-sectional grid surfaces contain 81 points from the hull to the outer boundary and 65 around the hull from the keel to the water surface. The closest grid surface concentric to the hull is about 10^{-5} body lengths from the hull surface putting the first layer of centroids adjacent to the hull at a boundary layer coordinate y^+ of about 5.

The grid must be adjusted to fit the developing water surface solution. A two-dimensional elliptic grid generating routine is used to carry out this process on cross-sectional grid surfaces. It was found that, as the calculations proceeded, some unrealistically steep wave slopes developed, usually adjacent to the hull, for which it was very difficult to generate a suitable grid. This arose because of the use of spatially varying time stepping to accelerate convergence. Therefore, between each grid adjustment, the flow solution is advanced with a fixed grid until such gradients are eliminated. Another approach would be to carry out time accurate computations.

FLOW SOLUTION

The DTNS codes were originally developed by J. Gorski (1988) at the David Taylor Model Basin and have recently been further developed by Gorski and others. The numerical methods on which the codes are based have been presented elsewhere and this paper will concentrate on the transom stern application. The RANS equations for steady incompressible flow are solved using the pseudo-compressibility approach. The equations are discretized with the finite-volume formulation. Second-order central differencing is applied to the viscous terms and third-order upwind differencing to the convective terms. The approximate factorization option for solving the resulting equations and the $k - \epsilon$ turbulence option are used for this study.

FREE-SURFACE BOUNDARY CONDTIONS

All lengths are rendered nondimensional through division by the length of the hull L and nondimensional velocities are defined by the hull's forward speed U. The two natural dimensionless parameters are the Reynolds number, $Re = UL/\nu$, and the Froude number, $Fr = U/\sqrt{gL}$ where ν is the kinematic viscosity and g is the gravitational acceleration. A coordinate system is fixed to the hull with its origin at the intersection of the bow and the undisturbed water level. The horizontal coordinates are x and y with x increasing toward the stern in the streamwise direction. The vertical coordinate z is positive above the undisturbed water level. The dependent variables are u,v and w (the velocities in the x, y and z directions); the dynamic pressure p; and the water surface elevation η. The dynamic viscous conditions of continuity of the three components of stress across the air/water interface are replaced by the widely-used inviscid conditions for a free surface:

$$p - z/Fr^2 = 0, \partial(u, v, w)/\partial z = 0 \text{ on } z = \eta(x, y, t) \quad (1)$$

where t is time (pseudo-time for this steady computation) and where atmospheric pressure is taken to be zero. The use of such inviscid conditions eliminates the small-scale effects of free-surface boundary layers, which have little influence on the large-scale waves, but does not preclude the main viscous/free-surface interaction of the hull boundary-layer wake with the stern waves. The kinematic condition that the water surface be a material boundary is:

$$\frac{\partial \eta}{\partial t} + u\frac{\partial \eta}{\partial x} + v\frac{\partial \eta}{\partial y} = w \text{ on } z = \eta(x, y, t) \quad (2)$$

Eq. 2 is discretized with third-order upwind differencing for consistency with the convective terms of the RANS equations and the same numerical solution procedures are employed. Eqs. 1 and 2 are boundary conditions within the RANS solution procedure and are applied along with the usual noslip, symmetry and farfield conditions on the appropriate boundaries. However, Eq. 2 is itself a partial differential equation and needs its own boundary conditions. Simple zero normal gradient conditions $\partial\eta/\partial n = 0$ are applied at all boundaries of the water surface except at the transom where the surface elevation is set equal to the transom depth. This is the high-speed assumption.

The treatment of the surface as a single-valued function of the horizontal coordinates eliminates wave breaking. Since models tests exhibit wave breaking near the bow and stern, some discrepencies are expected.

RESULTS

Calculations have been carried out at $Re = 1.8\text{x}10^7$ and $Fr = 0.4136$. This Froude number corresponds to a speed of 30 knots for the full-scale ship. Two model orientations are used in the computations - (1) fixed and (2) sunk and trimmed. In the fixed case the model is oriented in the position that it assumes naturally when floating at rest in calm water. In the sunk and trimmed case it is oriented in the position that it assumes in a model test where it is free to rotate and move vertically in response to the lift forces. The sinkage and trim results in very little change in the bow height but a lowering of the stern by about 3/4 of 1% of the model length. The fixed case is of interest for comparison with other computations (Telste and Reed, 1993) and the sunk and trimmed case is of interest for comparison with measured data. Computations were carried out on Cray mainframe computers. About 100 iterations (pseudo-time steps) could be accomplished in one hour of Cray C90 CPU time. Computations were carried to convergence first with the fixed starting grid to investigate the qualities of such a linearized solution. This took on the order of 20,000 iterations. Convergence was considered to be achieved when there was no noticeable change in the solution during 1,000 or more iterations. Starting from the linear solution, the grid was fit and refit to the water surface every few thousand iterations until convergence of this procedure was achieved. This took on the order of another 20,000 iterations. Automation of the process would result in large savings of iterations.

Computed wave contours for the fixed case are shown in Fig. 7. Contours plotted are integral multiples of 0.00125 with positive elevations represented by solid lines and negative by broken lines. The bow wave train consists of the bow wave itself with a very steep wave front, a trough near midship and a peak at $x = 1.2$ and $y = 0.3$. The results agree qualitatively with the contour plots of computed and measured data presented by Telste and Reed (1993). A wave trough is present near the hull at $x = 0.6$. This generates another wave train just inboard from the bow wave

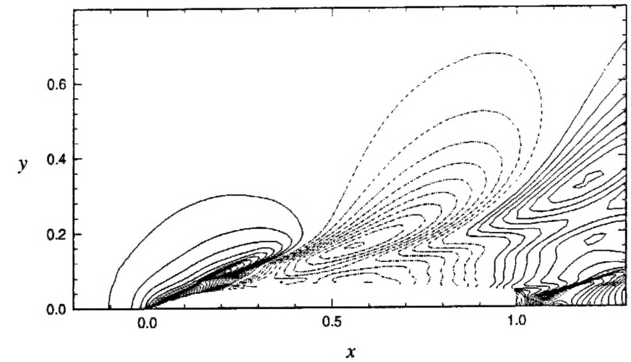

Figure 7. Contours of computed water surface elevation for fixed model.

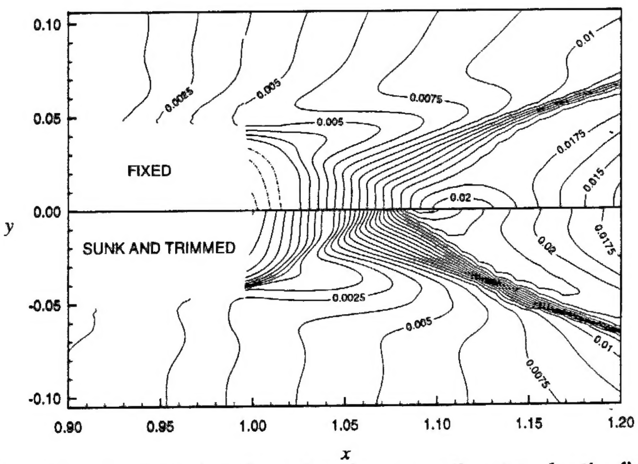

Figure 8. Computed surface elevations near the stern for the fixed and sunk and trimmed models.

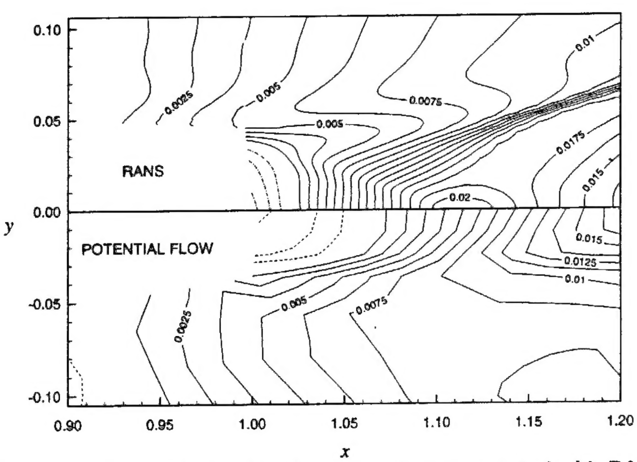

Figure 9. Comparison of surface elevations computed with RANS and potential flow for the fixed model.

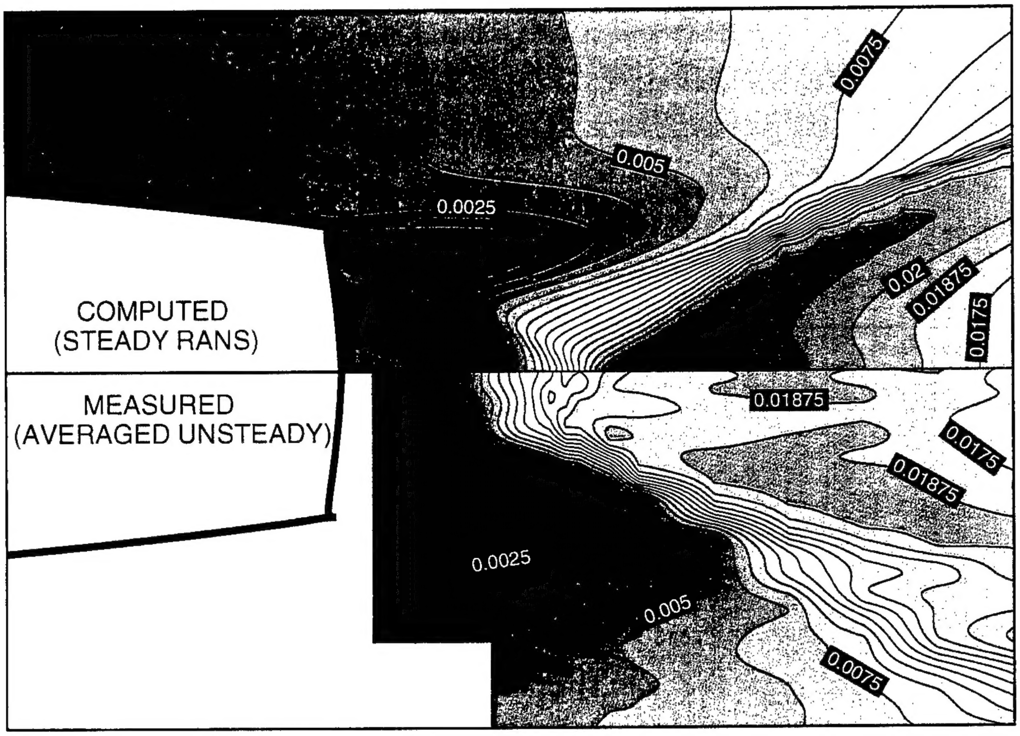

Figure 10. Computed and measured surface elevations near the stern for the sunk and trimmed model.

train. The stern region for both cases is displayed in Fig. 8. The water rises rapidly after it is released by the abrupt termination of the hull. A peak of surface elevation of about 0.02 model lengths is seen at about $x = 1.11$ at the centerline for the fixed case and a somewhat higher peak farther upstream is seen for the sunk and trimmed case. There are large v-shaped plateaus extending downstream from these peaks with leading slopes that are very steep especially between $x = 1.15$ and $x = 1.2$ at about $y = \pm 0.06$. Prominent troughs can be seen between the upstream portions of the steep slopes and the more gentle upward slopes farther out from the centerline.

Most of the widely-used potential flow codes employ linearized free surface conditions. The results obtained can depend heavily on the panelization and other details such as whether the linearization is about the free-stream flow or the double-model flow. Figure 9 presents a comparison of the current results for the sunk and trimmed case with a representative potential flow result from the method of Telste and Reed (1993). It can be seen that the potential flow computation predicts a peak much farther downstream and somewhat lower than that of the viscous flow. The downstream shift is due partially to the free-surface linearization but also to the absence of the boundary-layer wake. The flow in the wake is slowed and the water can rise more quickly than if it were moving relative to the hull at near the far-field velocity as in an inviscid model. That the viscous effects are significant was further verified by replacing the nonslip condition on the hull in the RANS computations with a slip condition. This eliminated the boundary layer and caused the stern wave peak to move downstream as in the potential flow.

It is encouraging that the RANS method yields results which appear to improve on the potential flow predictions. However, it must be verified that the new predictions are, in fact, better. The new results are similar to those obtained by Stern et al. (1995) for the FF1052 when they applied the same surface elevation boundary condition at the transom, but validation must ultimately lie in comparison with measured data. Fortunately, model tests carried out at David Taylor Model Basin in April 1997 have provided measured data, including, for the first time, details of the wave heights behind the transom.[2] For these tests, which were carried out at both $Fr = 0.28$ and $Fr = 0.41$, the model was fixed at each speed at the sinkage and trim measured for that speed in earlier tests (Ratcliffe and Lindenmuth, 1990). Figure 10 provides a comparison of the computed results with the measurements. Far way from the centerline, both indicate, a gently rising water surface, in the downstream direction, with excellent agreement in the contour locations. The presence of the plateau region, its predicted location, height, and shape, and the troughs outboard of its leading slope are verified by the measurements. The main difference between the predicted and measured results are due to the fact that the real flow is unsteady in the region of the stern wave peak. The flow develops to-

[2]The data obtained to date on Model 5415 are available at http://www50.dt.navy.mil/5415.

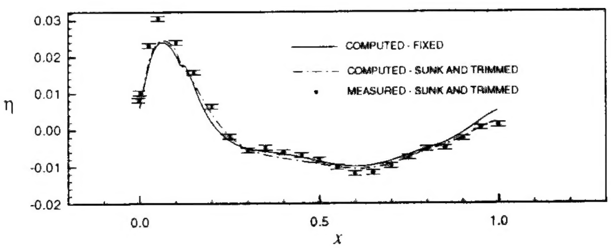

Figure 11. Comparison of computed and measured wave elevation at the hull.

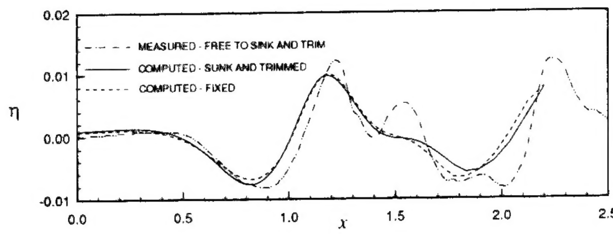

Figure 12. Comparison of computed and measured wave elevation at y = 0.324.

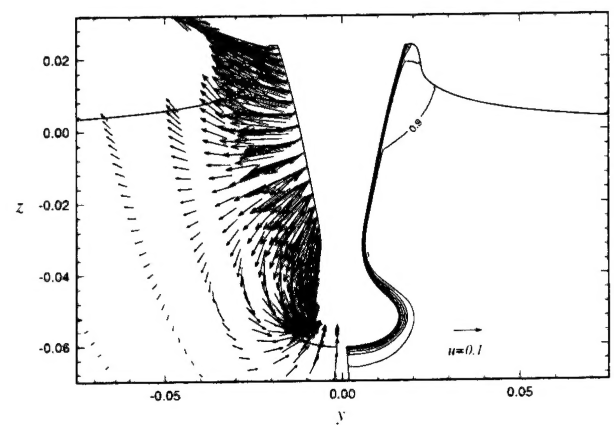

Figure 13. Computed crossflow (left) and streamwise velocities at x = 0.06 for the fixed case.

ward a sharp peak but then the water surface breaks, the peak is lowered, and foamy water rushes down the leading slope toward the transom. As it approaches the transom, this water loses momentum and then is swept back downstream. The peak tends to reform and the process repeats periodically. Thus the measured data, which are a time average throughout this process, do not show the sharp peak of the steady RANS prediction. Also, the water that is present at times on the leading stern wave slope raises the average elevations there and pushes the contours forward relative to the RANS prediction. Wave breaking along the side slope of the plateau leads to a spreading of the contours there which is not present in the RANS solution.

While there is unsteadiness in the model test it can be noted that it is apparently mostly limited to the stern wave area and that most of the remainder of the flow seems to be fairly steady. In particular, the flow appears to separate smoothly and steadily from the transom corners and the transom remains dry except for occasional splashes from the foamy water on the stern wave face. Thus a steady RANS computation which assumes a dry transom seems to have meaning for this high-speed case.

Comparison of wave height along the hull with measured data is presented in Fig. 11. The computed bow waves are somewhat lower than the measured. This is not surprising because of the presence of spray and breaking in the model test. The computed results for the fixed case show a positive elevation of about 0.005 at the stern. This is consistent with the inviscid results of Telste and Reed (1993). The computations for the sunk and trimmed case exhibit a lower elevation in this region than for the fixed case, in agreement with the measured data. The grid was designed to maximize accuracy near the hull and behind the transom. However, it is useful to evaluate the results in the region of expanding grid. A comparison with the earlier measured data is presented on a cut at $y = 0.324$ in Fig. 12. This cut passes through the outer edge of the bow wave and directly through the first peak of the bow wave train. Agreement is good considering that differences in wave amplitude, shape, and location are to be expected in tracking of a spectrum of waves into a region of expanding grid.

The flow near the bow is displayed in Fig. 13. The crossflow displays strong outward and upward flow at the top and strong downward and inward flow near the tapering bow dome. The streamwise velocity contours show a thin boundary layer on the hull proper with a thickening boundary layer on the bow dome. Fig. 14 shows the flow field just upstream from the transom. There is a thick boundary layer, the remnant of the bow dome wake and an inward and upward flow due to the tapering of the hull. The flow field in Fig. 15, just downstream from the transom, shows the boundary-layer wake at the water surface. There is enhanced upward flow and strong inward flow at about $x = \pm 0.04$, both due to the abrupt release of the water from the restraining influence of the hull. Fig. 16 shows a cross section of the plateau behind the stern wave peak. Slight downward flow near the centerplane gives way to strong upward and outward flow near the steep wave front.

The scope of this project has not allowed computational demonstration of convergence with respect to grid spacing. Preliminary results, obtained with a coarse grid (135x41x41), when compared with the results from the fine grid, showed a loss of accuracy in the higher wave frequencies. While it is likely that the current results from the fine grid retain some inaccuracies in the highest frequencies, es-

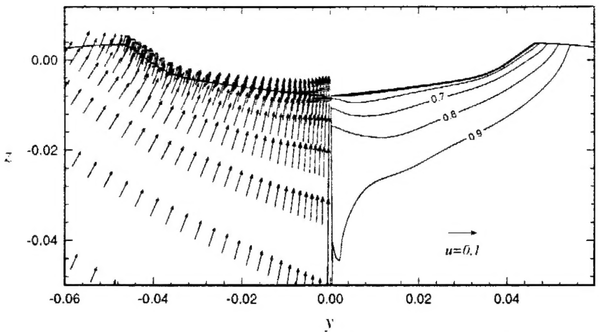

Figure 14. Velocity field at x = 0.97.

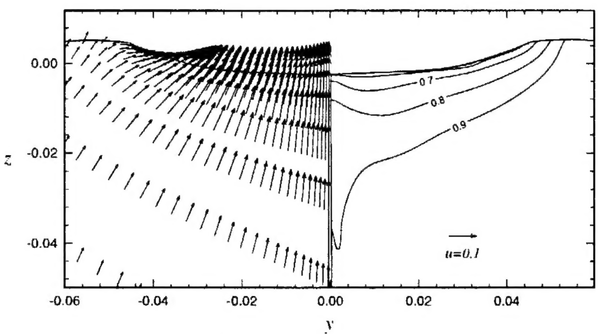

Figure 15. Velocity field at x = 1.01.

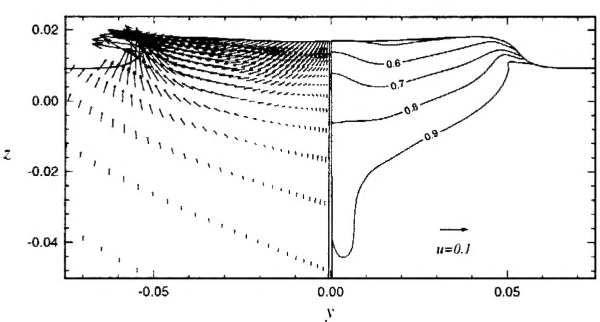

Figure 16. Velocity field at x = 1.16.

pecially in the far field (Fig. 12), the comparison with the measured data indicates that the fine grid sufficiently resolves the dominant features in the main regions of interest near the hull and water surface.

CONCLUSIONS

These results demonstrate the effect of a strong viscous/free-surface interaction. The very encouraging comparisons with measured data serve to justify the combination of RANS and free-surface computational technologies for surface ship analyses. It is notable that the RANS flow solver needed no further development for this challenging application. In fact, the code was essentially the same used for the Series 60 hull and, for that matter, for submerged bodies. This is a demonstration of the utility of a generalized multiblock code. By far the bulk of the work involved devising and implementing a grid generation strategy that could handle very steep wave slopes. These results should serve as a benchmark, and as a supplement to the measured data, for comparison with results from other generalized RANS/free-surface codes now under development(Beck et al., 1996). These new codes are ultimately aimed at treating the complete speed range and including unsteady flow effects. However, it is useful to demonstrate the accurate performance of new tools first on simpler problems before tackling the more complex cases where such demonstration is much more difficult.

Because of remaining challenges, such as flow recirculation behind a wet transom and wave breaking, it will be quite some time before highly-accurate RANS analyses of transom stern flows are routine.

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